

First Detection of Cosmic Structure in the 21-cm Intensity Field

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ABSTRACT

We present the first statistically significant detection of cosmic structure using broadly distributed hydrogen radio emission. This is accomplished using a cross correlation with optical galaxies. Statistical noise levels of $20\mu\text{K}$ are achieved, unprecedented in this frequency band. This lends support to the idea that large volumes of the universe can be rapidly mapped without the need to resolve individual faint galaxies, enabling precise constraints to dark energy models. We discuss strategies for improved intensity mapping.

1 INTRODUCTION

Many of the outstanding questions in cosmology can be addressed using maps of structure in the universe. Three dimensional maps can reveal the dynamics of the expansion, and are especially useful to study the effects of dark energy. Previously, the only known way to obtain a 3D map of the structure in the universe is via galaxy redshift surveys, that is by isolating millions of individual galaxies, recording spectra for each and determining each redshift. Galaxies appear fainter the further away they are, which makes their measurement progressively more expensive as the survey extends to higher redshift.

On the other hand, it may be possible to directly map 3D structure at high redshift by measuring line emission with coarse resolution. In this scheme the blended emission of many galaxies is collected together allowing large scale structure to be studied even though few galaxies are individually detectable. Here the aggregate emission is treated as a continuous 3D intensity field so we call this strategy “Intensity Mapping”.

Intensity mapping has a distinct advantage over redshift survey techniques because of the use of detection thresholds in redshift surveys. Galaxies are typically not entered into a redshift catalog unless they are detected with high confidence. Often a $> 5\sigma$ threshold is set for inclusion. By using only the 5σ peaks the galaxy survey throws away the great majority of the emission. In contrast, in the intensity mapping scheme one measures correlations within an intensity field. Here no threshold is needed and all the emission is used, allowing large volumes to be rapidly surveyed.

If the goal is the study of primordial structure, map resolution finer than 10 Mpc is not useful. Features of size smaller than this may have been imprinted early in the big bang but those early imprints have been erased by more recent gravitational motions. At 10 Mpc resolution a typical

3D map pixel contains many galaxies, making searches for their aggregate emission promising.

Several recent papers have proposed using Intensity Mapping as a tool to trace the evolution of dark energy (Chang et al. 2007; Wyithe & Loeb 2008). Large scale (> 10 Mpc) structure maps have imprinted in them a small periodic density variation due to Baryon Acoustic Oscillations (BAO). These are relics of the prominent peaks seen in the spatial power spectrum of the cosmic microwave background. The baryon oscillation wavelength serves as a co-moving “standard ruler”. Measurement of the angular (and redshift space) wavelengths of these oscillation as a function of redshift will allow precise measurement of the kinematics of the expansion. In most cosmic evolution models dark energy only becomes dynamically important at $z < 2$, so measurements at such redshifts are needed to distinguish among these models.

The 21cm hydrogen transition is the dominant spectral line at frequencies less than 1420 MHz, and is an isolated transition which allows a direct translation of the frequency of a source into its redshift (distance). This means the 21cm transition is well suited for a three dimensional intensity mapping experiment.

The challenge in such an experiment is to detect cosmic structure in the 3D 21 cm intensity field beneath the much brighter flux from continuum sources. Here we show that detection of cosmic structure via 21 cm intensity mapping is indeed possible. We make this initial detection by use of a template provided by an optical galaxy redshift survey.

2 DATA

The nearby southern sky was mapped in the redshifted 21cm line as part of the HIPASS survey (Barnes et al. 2001). This program was designed under the traditional galaxy redshift

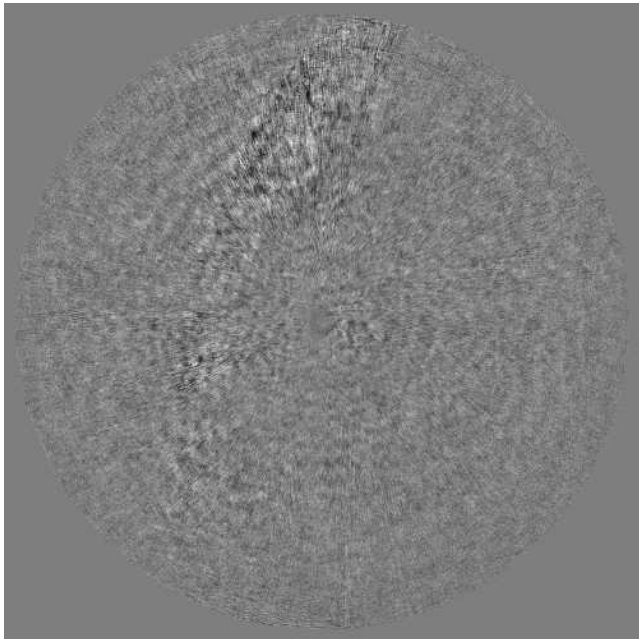


Figure 1. The HIPASS data cube $R < 127h^{-1}$ Mpc, projected in a cartesian coordinate system towards the south pole.

survey scheme in which individual galaxies are detected at high confidence, these positions are cataloged and the search for cosmic structure uses the catalog. Here we do not use the HIPASS galaxy catalog (HICAT), but instead use 21 cm spectral intensity data. The HIPASS survey extends to a distance of $127 h^{-1}$ Mpc and covers all declinations south of $+25.5^\circ$.

Figure 1 shows a cartesian projection of the HIPASS intensity field. The region shown is $254h^{-1}$ Mpc across and image pixel size corresponds to the observation beam size $0.5h^{-1}$ Mpc. The large scale structure of the universe as mapped by the galaxies (see Figure 2) is not apparent to the eye in this 21 cm image. Instead two types of features stand out: ring structures, likely due to discreteness in the declination scan strategy, and residual continuum emission from the Milky Way, which appears as a broad diagonal structure on the left half of the image. The structure visible in this map is due to cleaning artifacts, including scan to scan calibration variation and incomplete continuum source subtraction.

Much of the HIPASS volume was also surveyed optically. The six degree field galaxy redshift survey (6dFGS; Jones et al. (2004, 2005)) is a redshift survey of the southern sky. The full 6dFGS contains more than 120,000 redshifts, and was collected from 2001 to 2005. The majority of targets were taken from the 2MASS catalog.

6dFGS contains 27417 galaxy redshifts in the region of overlap with HIPASS. Their spatial locations are shown in figure 2. Unlike the 21 cm image the typical features of redshift maps are apparent, including the filamentary structure, and velocity distortions, which appear radial in this projection. The figure prominently displays the cosmic web of large scale structure.

Just as the eye is drawn to the continuum residuals in figure 1, the autocorrelation of the HIPASS data is dominated by spurious correlations due to these structures. Sam-

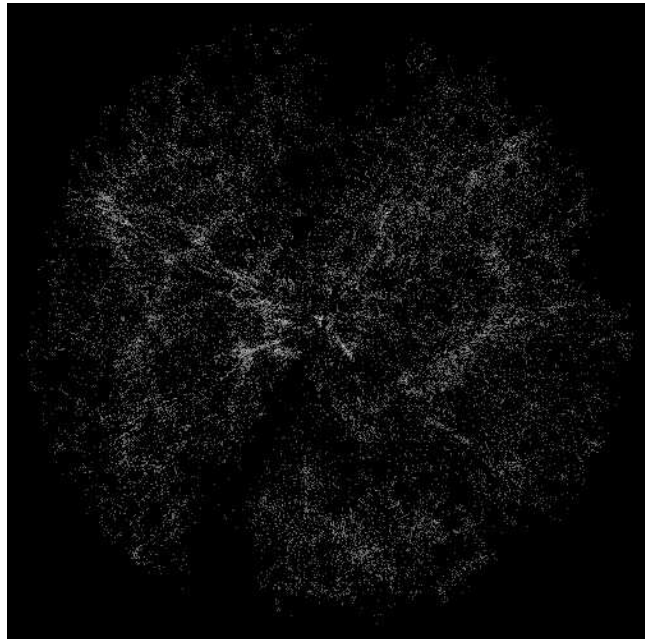


Figure 2. The 6dFGS catalog for $R < 127h^{-1}$ Mpc, also projected towards the south pole. The missing wedges are the galactic plane.

pled with the $0.5 h^{-3}$ Mpc³ pixels we used, the variance is about $(3.6 \text{ mK})^2$. If these variations were uncorrelated between pixels, this would average down when larger structures were examined. For example, when rebinned to cells of the nonlinear length scale, i.e. cells of $\sim 10 h^{-1}$ Mpc radius, uncorrelated noise would go down by $\sqrt{\sim 8000}$, resulting in a pixel noise around $40 \mu\text{K}$. This would in principle yield a signal-to-noise comparable to the sample variance, leading to a sample variance limited power spectrum. Over the HIPASS survey volume, there are 1000 such cells, which could lead to a 30σ detection of the large scale structure signal in the autocorrelation function. In practice, however, the noise does not reduce as one averages on larger scales. Figure 3 shows the measured autocorrelation in a redshift shell of thickness $13 h^{-1}$ Mpc, centered at $95 h^{-1}$ Mpc distance. The crosses with error bars are the measured correlation, which is much larger than the expected signal (solid line, described below). The excess variance is presumably due to the residual from incomplete foreground subtraction.

The HIPASS observing strategy was designed to detect galaxies, rather than extended 21 cm structures. To bring out the cosmic structure despite the continuum artifacts we computed the cross correlation of the 21 cm intensity field with the positions of the optically detected galaxies. In the limit of a large survey volume, in such a cross correlation, the contribution from radio continuum residuals should average to zero, as long as the optical and radio surveys do not share common artifacts. If there are no noise correlations between the two surveys, averaging over the $N = 27417$ 6dFGS galaxies, one expects the statistical noise to reduce by \sqrt{N} to $22 \mu\text{K}$.

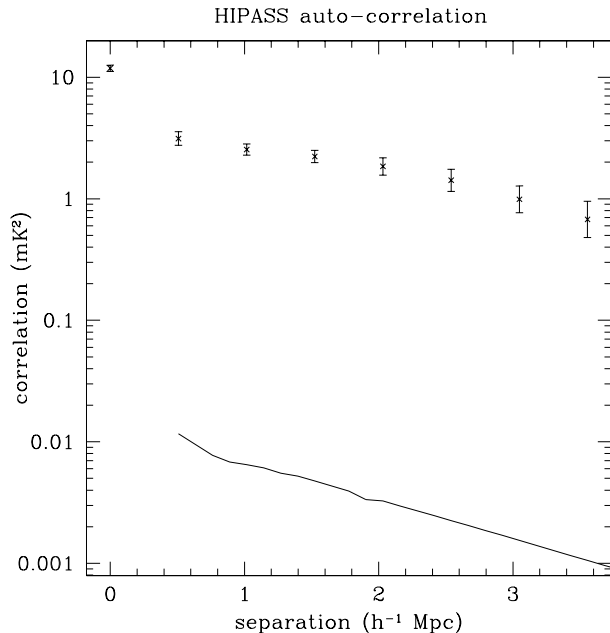


Figure 3. The auto correlation of the HIPASS data cube, in a shell of thickness $13 h^{-1}$ Mpc, centered at $95 h^{-1}$ Mpc distance. The solid line is the model prediction (see text). The signal is due to residual foreground subtraction. The vertical axis is a variance, so the residual foreground fluctuations of $\sim mK$ is about a factor of ten larger than the expected large scale structure signal.

3 CROSS-CORRELATION

We computed a radio-optical cross correlation, starting by gridding both the 6dFGS galaxies and the HIPASS data on a regular grid, 500 grid cells wide, with grid spacing of $0.5 h^{-1}$ Mpc. Our goal is to detect cosmic structure in the portion of the survey where individual galaxies are difficult to detect with confidence. We only used data with distances greater than $63 h^{-1}$ Mpc, i.e. distances at least half way to the survey edge. This includes the majority (7/8th) of the survey volume but contains only 7% of the 4315 detected HICAT galaxies.

The HIPASS data we used had already been filtered both spatially and spectrally. The data were recorded while sweeping the telescope in declination, and the median of neighboring strips in declination was subtracted from each beam-width region. This spatial filter suppresses structures in the declination direction bigger than the beam, which is about $0.5 h^{-1}$ Mpc at a typical distance of $100 h^{-1}$ Mpc. In order to measure a largely unsuppressed correlation, we only included pairs of HIPASS and 6dFGS cells with a transverse separation of less than $0.7 h^{-1}$ Mpc. The frequency domain was also filtered to remove continuum point sources. This is accomplished by removing all flux from each pixel that fits a low order polynomial. Because of the slow variation with frequency of the spectra of the continuum sources they are strongly attenuated, leaving behind the 21 cm line emission.

Figure 4 shows the measured cross correlation. We see a significant detection at separations up to $3 h^{-1}$ Mpc. At larger separation the correlation signal is strongly suppressed by the spatial filtering. The signal is a measure of the collective HI emission of volumes adjacent to 6dFGS galaxies. The strong cross correlation at zero separation is

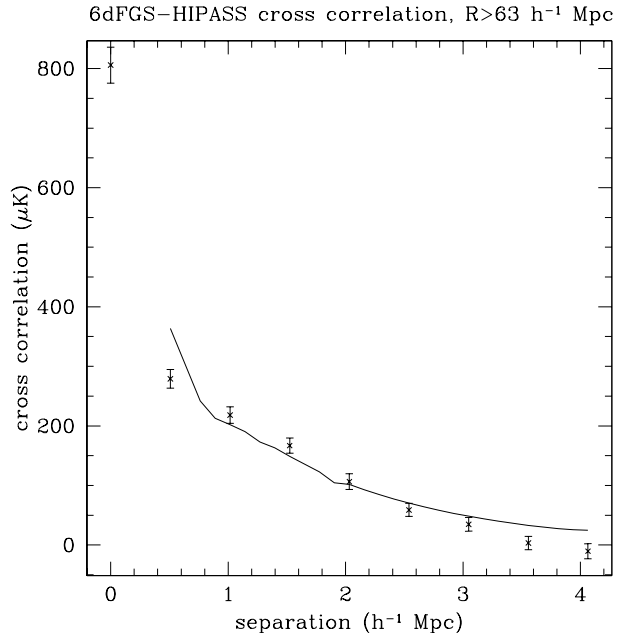


Figure 4. The correlation function of hydrogen 21 cm emission when stacked around optically selected galaxies from the 6dFGS. The solid line is a standard clustering model. The point at zero separation is the mean flux from 6dF galaxies, while points at larger separations measure the associated surrounding large scale structure. HI emission from the 6dF galaxies could spill up to $1 h^{-1}$ Mpc into neighboring bins at the $\sim 20 \mu K$ level.

the HI emission from the 6dFGS galaxies themselves. The solid line is an estimate of the expected correlation, using the 2dFGS model (Madgwick et al. 2003). This model adopts a power law form for the cross correlation function $\xi = 35(r/r_0)^{-1.8} \mu K$ with a standard correlation length $r_0 = 5.5 h^{-1}$ Mpc (Peebles 1993). 6dFGS galaxies are preferentially early type, and typically have a longer correlation length than our choice for r_0 . HIPASS sources are preferentially gas rich late type, which typically have a shorter correlation length. We selected a mean value. A bias of $b = 1$ was assumed. The average 21 cm sky brightness was taken as $35 \mu K$ (Chang et al. 2007), using $\Omega_{HI} = 0.0004$ (Zwaan et al. 2005). A radial velocity dispersion was also assumed, which is convolved with the correlation function. This dispersion value was the only free parameter, chosen to fit the data. The best fit pairwise dispersion is 200 km/sec . The power law correlation model does not work at zero separation, so that data point was excluded from the fit.

The noise level of the cross correlation is less than $20 \mu K$. This uncertainty was determined by subdividing the data set and comparing the results of the subsets. A direct measurement of the BAO signal was made by Eisenstein et al. (2005), at a correlation amplitude wiggle of ~ 0.01 and a lag of $109 h^{-1}$ Mpc. In the units of figure 4, this corresponds to an amplitude of $\sim 0.3 \mu K$, so a factor of 30 larger in separation and a factor of 100 smaller in the current achieved noise amplitude. The maximum radius of the HIPASS survey is too small to search for features with such a large wavelength.

4 FUTURE PROSPECTS

A program to precisely measure baryon oscillation—and thereby to study dark energy (Kolb & et al. 2006; Seo & Eisenstein 2007)—requires a volume 10^4 that of the HIPASS data set. This would require a dedicated intensity mapping survey program, and the success reported here may encourage 21 cm observers to rapidly proceed with such a program. There will be no optical survey of such a large volume available for cross correlation for many years to come. However, while waiting for these surveys it still may be possible to detect and study cosmic structure in the 21 cm intensity field by autocorrelation. This will require much more complete continuum removal than has been accomplished so far in the HIPASS data set.

Several programs¹ are already underway to measure the collective 21cm emission during the epoch of reionization, $z > 6$, when the neutral fraction of the universe was closer to unity. At the low frequency of these observations the continuum sources are very bright, so under these programs effective tools for continuum removal are being developed.

In principle, the Baryon Acoustic Oscillation signal could be detected at redshifts near that of the reionization. Assuming the universe was matter dominated at such high redshifts, the position of the BAO peaks is directly tied to the position of the peaks at the CMB power spectrum. The BAO peak positions should be redshift independent between $z \sim 1100$ and $z \sim 6$. Any deviation from this expected peak position would amount to detection of dynamical influences of dark energy at very early times. This is unexpected, and so would be intriguing if found.

A low ($z < 2$) redshift 21 cm Intensity Mapping program would share many features with CMB surveys, which do detect baryon oscillation via autocorrelation (see Tristram & Ganga (2007) for a recent review, and references therein). On existing single-dish 21 cm telescopes, the observing strategy would be to scan in azimuth at constant elevation, but to do this for each field at a several local hour angles, thereby creating a cross-linked data set. Such observing techniques and their analysis pipelines have developed over the forty year history of CMB observations, and are very effective (Spergel et al. 2007; Reichardt et al. 2008; Jones et al. 2006). Such a program might succeed in detecting the cosmic web structure but the sky coverage needed for precise BAO studies may be difficult to obtain using existing single dish telescopes.

One approach to rapidly map large areas of sky is to use interferometers, which offer excellent instrumental stability and mapping speed. Since one is searching for large angular scale features, existing interferometers such as the Very Large Array, are not appropriate since they are insensitive to large angular scales. Instead, a dedicated compact array, in the spirit of successful CMB experiments like DASI (Kovac et al. 2002) and CBI (Padin et al. 2002),

could achieve an all sky map of most of the visible universe (Chang et al. 2007; Wyithe & Loeb 2008).

5 CONCLUSIONS

We report the first detection of cosmic structure via extended 21 cm hydrogen emission. Optically measured galaxy positions in three dimensions were used as a finding chart to locate the density peaks of cosmic structure, and the 21 cm excess brightness is detected at up to $3 h^{-1}$ Mpc distance from these galaxies. Due to the spatial filtering in the HIPASS maps, most of the correlation signal comes from correlations along the line of sight, rather than transverse structure. The detection is a cross correlation, and represents a first step towards mapping the cosmic structure using 21cm emission.

Proposed programs to measure baryon oscillations via 21 cm intensity mapping will need to measure autocorrelations of 21 cm flux at separations larger than $100 h^{-1}$ Mpc. While the HIPASS data set we used covers a volume too small to test such plans directly, the low noise level of the correlation we measure is encouraging.

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¹ Giant Metrewave Radio Telescope (GMRT; <http://www.ncra.tifr.res.in>), Low Frequency Array (LOFAR; <http://www.lofar.org>), Murchison Widefield Array (MWA; <http://web.haystack.mit.edu/arrays/MWA>), Primeval Structure Telescope (PAST; [http://web.phys.cmu.edu/~sim\\$past/](http://web.phys.cmu.edu/~sim$past/)), and Square Kilometre Array (SKA; <http://www.skatelescope.org>).

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